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ASTROPHYSICAL LIMITS ON GRAVITINO MASS

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Abstract

We calculate exotic cooling rates of stars due to photo-production of light particles (mostly scalars and pseudoscalars) which originate from the hidden sector of no scale supergravity theories. Using this we can restrict the gravitino mass $m_{3/2}$. The range of eliminated values of $m_{3/2}$ stretches over six orders of magnitude and is given by $2 \times 10^8 < \frac{m_{\tilde{g}}}{m_{3/2}} < 6 \times 10^{13}$, $m_{\tilde{g}}$ being the gluino mass. Combining our result with the earlier analysis from colliders ($\frac{m_{\tilde{g}}}{m_{3/2}} < 2.7 \times 10^{14}$) we conclude that $\frac{m_{\tilde{g}}}{m_{3/2}} < \mathcal{O}(10^8)$ except for a narrow window around 10^{14}. Together with the current experimental limit on $m_{\tilde{g}}$ and cosmological constraints on $m_{3/2}$, albeit model dependent, our analysis shows that a light gravitino is on the verge of being ruled out.

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In the last twenty years a lot of effort went into establishing a signal of a theory which we believe would replace the standard $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ model at high energies. In the order of the increasing scale these theories are likely to be: global supersymmetry [1], supersymmetric Grand Unified Theory (GUT) [2] and supergravity [3] which, being non-renormalizable, should in principle be only an approximate version of something more fundamental, like superstrings. Whereas we hope that the effects of global supersymmetry will manifest themselves around 1 TeV scale the physical effects of GUT theories which are testable at present in laboratory experiments are only a few (to mention the standard example of proton decay or the existence of a monopole). Up to now searches for supersymmetric particles and proton decay have resulted in lower bounds on their masses and an upper bound on proton lifetime [4]. The presence of supergravity theory at Planck scale justifies the soft supersymmetry breaking terms in the global theory i.e. effectively reduces the number of free parameters which via renormalization group equation can be scaled down to present energies. A more direct signal of the usual supergravity is practically non-existent. Though, in general, not a serious problem, this can be a bit intriguing as supergravity theories are not unique due to the arbitrariness of the Kähler potential. It has been, however, realized that a superlight gravitino ($\tilde{G}$) could be the harbinger of physics from the hidden sector of supergravity [5]. A superlight gravitino field ψ_μ acts as spin-1/2 Goldstino χ with $\psi_\mu = i\sqrt{2/3}m_{3/2}^{-1}\partial_\mu\chi$. In momentum space the spin summed density matrix corresponding to this longitudinal part of ψ_μ takes the form $p_\mu p_\nu/m_{3/2}^2$ which effectively, when coupled to a gauge boson V ($V = \gamma,\ g,\ Z$) and a gaugino $\tilde{V}$, enhances the coupling by a factor $\dfrac{m_{\tilde{V}}}{m_{3/2}}$. More precisely, since $\tilde{G}$ is the superpartner of graviton it couples to particles with the strength proportional to $\kappa = \sqrt{8\pi G_N} = 4.11 \times 10^{-19}\ GeV^{-1}$ (G_N is Newton's gravitational constant). Hence the effective net coupling turns out to be $\kappa m_{\tilde{V}}/m_{3/2}$. Later the idea of a superlight

gravitino was embedded in the no scale supergravity theories [6]. Special attention was drawn to the super-Higgs mechanism in these type of theories and it was found that the coupling of certain light scalar ($\mathcal{S}$) and pseudoscalar ($\mathcal{P}$) to gauge bosons is also proportional $\kappa(m_{\tilde{V}}/m_{3/2})$ [7]. These particles ($\mathcal{S}$ and $\mathcal{P}$), in the physical spectrum of the theory, are members of a chiral superfield in the hidden sector. Their spin-1/2 superpartners are Goldstinos which get eaten up by the gravitino. Needless to say that a signal originating from the hidden sector of such a supergravity theory would be quite spectacular, more so as the relevant coupling is directly proportional to the gravitational constant G_N. Indeed bounds (to be discussed later) on $m_{3/2}$ have been put by examining exotic decay processes and scattering reactions involving $\mathcal{S}$, $\mathcal{P}$ and $\tilde{G}$ at collider energies [8–11]. It is worth mentioning here that what makes bounds on gravitino mass even more interesting are hints from cosmology that point in the direction of either a light gravitino with mass $m_{3/2} < 1\ keV$ or a heavy one with $m_{3/2} > 1\ TeV$ [12,13]. In this letter we eliminate the parameter space of $m_{3/2}$ further by investigating exotic cooling processes of stars like the Sun and Red Giants. In particular these additional cooling rates are due to the photon reactions like $\gamma e^{\pm} \to \gamma + \mathcal{S}/\mathcal{P}$ (Primakoff process) and $\gamma\gamma \to \tilde{G}\tilde{G},\ \mathcal{S}\mathcal{S},\ \mathcal{P}\mathcal{P}$.

The interaction lagrangian relevant for single and two photon processes is [14,7]

$$\begin{aligned} e^{-1}\mathcal{L}_{int} = &-\frac{\kappa}{4}\sqrt{\frac{2}{3}}\Big(\frac{m_{\tilde{\gamma}}}{m_{3/2}}\Big)\Big[\mathcal{S}\mathcal{F}^{\mu\nu}\mathcal{F}_{\mu\nu} \quad + \quad \frac{1}{2}\mathcal{P}\varepsilon^{\mu\nu\rho\sigma}\mathcal{F}_{\mu\nu}\mathcal{F}_{\rho\sigma}\Big] \\ &+ \frac{1}{2}\varepsilon^{\mu\nu\rho\sigma}\bar{\psi}_\mu\gamma_5\gamma_\nu\mathcal{D}_\rho\psi_\sigma \quad + \quad \frac{1}{4}\kappa\bar{\lambda}\gamma^\sigma\sigma^{\mu\nu}\psi_\sigma\mathcal{F}_{\mu\nu} \\ &- i\frac{\kappa}{2}\sqrt{\frac{3}{2}}\Big[m_{3/2}\mathcal{S}\bar{\psi}_\mu\sigma^{\mu\nu}\psi_\nu \quad + \quad \frac{1}{2}\varepsilon^{\mu\nu\rho\sigma}\bar{\psi}_\mu\gamma_\nu\psi_\rho\partial_\sigma\mathcal{P}\Big] \end{aligned} \tag{1}$$

where e is the determinant of the vierbein and $\mathcal{D}_\mu$ is the covariant derivative expressed in terms of the spin connection $\omega_{\mu ab}$ viz. $\mathcal{D}_\mu\psi_\nu = (\partial_\mu - i/4\omega_{\mu ab}\sigma^{ab})\psi_\nu$. λ is the photino field and $m_{\tilde{\gamma}}$ is the mass parameter which enters the full lagrangian in the form of the bilinear $m_{\tilde{\gamma}}\bar{\lambda}\lambda$. $\mathcal{F}_{\mu\nu}$ is the usual electromagnetic stress tensor. In general, one

can have more than one pair of $\mathcal{S}$ and $\mathcal{P}$ particles, but for practical purposes it is convenient to take just one pair.

The first two terms in eq.(1) are sufficient to calculate $\gamma e \to \gamma + \mathcal{S}/\mathcal{P}$. The rest of the interaction terms appears in the calculation of $\gamma\gamma \to \tilde{G}\tilde{G}$ where we have two diagrams with $\tilde{\gamma}$ in t- and u-channel as well as three s-channel diagrams with G, $\mathcal{S}$, $\mathcal{P}$ in the intermediate state. Note also that since the dimension 5 operators $\mathcal{S}\mathcal{F}\cdot\mathcal{F}$ and $\mathcal{P}\mathcal{F}\cdot\tilde{\mathcal{F}}$ contain higher order derivatives they are expected to violate tree level unitarity at some scale. A number of papers [7,9] have been devoted to this subject. The violation of tree level unitarity need not be a serious embarrassment of the theory since supergravity should not be considered as the last word in the physics of Planck scale. We view it rather as an approximation to the latter. Therefore as long as we do not stretch the involved energies beyond a critical value (in astrophysical applications this is never the case) the results are still trustable.

At tree level $\mathcal{S}$ and $\mathcal{P}$ are strictly massless. They can, however, acquire mass radiatively, mostly through loops with intermediate gluons. Their mass is estimated to be [15]

$$m_{\mathcal{S}/\mathcal{P}} \;\sim\; \kappa \left(\frac{m_{\tilde{g}}}{m_{3/2}}\right) \Lambda^2_{QCD} \tag{2}$$

Commonly one assumes the equality of gaugino masses at a high unification scale. Via renormalization group equation this assumption leads to the following mass relation at lower energies [16]

$$m_{\tilde{\gamma}} \;\simeq\; \frac{8}{3}\,\frac{\alpha_{em}}{\alpha_s}\, m_{\tilde{g}} \;\simeq\; \frac{1}{6}\, m_{\tilde{g}} \tag{3}$$

In what follows we will use eq.(3) as a guiding relation between $m_{\tilde{g}}$ and $m_{\tilde{\gamma}}$. We mention this explicitly as in view of eqs.(2) and (3) any bound on $\left(\frac{m_{\tilde{\gamma}}}{m_{3/2}}\right)$ can be translated into a bound on $m_{\mathcal{S}/\mathcal{P}}$ and vice versa. Furthermore, the coupling $g_{\mathcal{S}/\mathcal{P}\gamma\gamma}$

depends now linearly on $m_{\mathcal{S}/\mathcal{P}}$ in which case astrophysical limits on $m_{\mathcal{S}/\mathcal{P}}$ and $g_{\mathcal{S}/\mathcal{P}\gamma\gamma}$ should not be treated independently, a situation encountered also in axion physics.

The best model-independent bound on $\left(\frac{m_{\tilde{\gamma}}}{m_{3/2}}\right)$ obtained so far comes from e^+e^- colliders in the reaction $e^+e^- \to \gamma +$ nothing realized in the model by $e^+e^- \to \gamma\mathcal{S},\ \ \gamma\mathcal{P}$ [11]. A slightly model dependent bound, assuming $m_{\tilde{q}} > m_{\tilde{g}}$, can be derived in $p\bar{p}$ reactions studying the events of monojets and dijets with missing p_T [10]. This would be the signal of processes like $p\bar{p} \to g\mathcal{S},\ \ g\mathcal{P},\ \ \tilde{g}\tilde{g},\ \ \tilde{g}\tilde{G}$. The outcome of the two analyses yields

$$\left(\frac{m_{\tilde{\gamma}}}{m_{3/2}}\right)_{e^+e^-} \; < \; 1.8 \times 10^{15} \quad , \quad \left(\frac{m_{\tilde{\gamma}}}{m_{3/2}}\right)_{p\bar{p}} \; < \; 4.5 \times 10^{13} \tag{4}$$

corresponding to $m_{\mathcal{S}/\mathcal{P}} = 0.18\ MeV$ and $m_{\mathcal{S}/\mathcal{P}} = 4.4\ keV$, respectively ($\Lambda_{QCD} = 200\ MeV$). Both limits are better than the older Fayet's bound of 4.3×10^{15}.

The importance of restricting gravitino mass becomes also clear in light of the cosmological arguments given in [12,13]. Based on the observed bound on cosmological mass density and a Helium synthesis there are strong indications, quite independent of the specifics of an underlying supergravity theory, that

$$1\, keV \;\not<\; m_{3/2} \;\not<\; 10\, TeV \tag{5}$$

i.e. cosmology seems to favour either a light or a heavy gravitino. This restriction can be evaded by assuming an inflationary scenario with low reheating temperature [17]. This is, however, incompatible with baryogenesis from GUT theories which should occur at higher temperature [18]. A natural way out would be to produce baryon asymmetry through anomalous processes at electroweak scale [19]. Whether this is possible remains still an open question, but there are convincing arguments which show that the Higgs mass required for such scenario is in contradiction with recent LEP limits on M_{Higgs} [19]. The baryon asymmetry produced at GUT scale

with $B-L$ consevation gets washed out by the anomalous processes unless e.g. some lepton number violating processes are operative [20]. An alternative would be a GUT theory with no $B-L$ conservation where the baryon asymmetry can, in general, survive the electroweak transition.

Yet another way to avoid restriction (5) can be broadly described as belonging to the class of R-parity breaking theories [21]. In any case, we will envisage a change of our understanding of supergravity theories and/or cosmology, should the limit given in eq.(5) be violated.

Before applying astrophysical processes [22] to restrict the gravitino mass let us make some general comments on what is to be expected in such an analysis. From the core temperature of the stars like Sun ($T_{\odot} \simeq 1\ keV$), Red Giants ($T_{RG} \simeq 10\ keV$), White Dwarfs ($T_{WD} \simeq 2\ keV$) [23] and a newly born Neutron Star in a Supernova explosion [24] ($T_{SN} \simeq 30\ MeV$) it becomes evident that only light particles (in the extreme case with a few MeV mass) can contribute to the cooling processes of stars. Plasmon effects will suppress single and two gamma processes (relevant in our case) in White Dwarfs and Supernovae. Hence we are left with the Sun and the Red Giants where the available energy is at most few keV. Moreover, if the particles $\mathcal{S}$ and $\mathcal{P}$ become too heavy their relatively fast decay will preclude the possibility of their causing any exotic cooling. From the width

$$\Gamma(\mathcal{S}/\mathcal{P} \to \gamma\gamma) = \frac{1}{96\pi}\kappa^2 \left(\frac{m_{\tilde{\gamma}}}{m_{3/2}}\right)^2 m_{\mathcal{S}/\mathcal{P}}^3 \sim \frac{1}{3456\pi}\left(\frac{m_{\mathcal{S}/\mathcal{P}}}{\Lambda_{QCD}}\right)^4 m_{\mathcal{S}/\mathcal{P}} \tag{6}$$

we can estimate the distance λ_{flight} traveled by the particle in the rest frame of the star in meters

$$\lambda_{flight} \simeq 3 \times 10^{15} \left(\frac{keV}{m_{\mathcal{S}/\mathcal{P}}}\right)^6 \left(\frac{\omega'}{keV}\right) \left(1 - \left(\frac{m_{\mathcal{S}/\mathcal{P}}}{\omega'}\right)^2\right)^{1/2} m \tag{7}$$

where ω' is the energy of the produced particle. Let us apply eq. (7) to the Primakoff process on a target $Z = e,\ p$ etc. In the case of interest where the initial photon

energy ω_γ is T_{star} we have $m_Z >> \omega_\gamma >> M_{\mathcal{S}/\mathcal{P}}$. The four momentum transfer q is then very low, $m^2_{\mathcal{S}/\mathcal{P}}\left(\frac{m^2_{\mathcal{S}/\mathcal{P}}}{4\omega^2_\gamma}\right) \leq |q^2| \leq 4\omega^2_\gamma$, such that $\omega_\gamma \sim T_{star} \sim \omega'$. If we take $m_{\mathcal{S}/\mathcal{P}} \sim 10^{-1}T_{star}$ we get for the Red Giants $\lambda_{flight} \simeq 10^{16}m$. The other extreme example of a Supernova with $m_{\mathcal{S}/\mathcal{P}} = 1\ MeV\ (4\ keV)$ gives $\lambda_{flight} = 90\ (2\times 10^{16})\ m$.

The above arguments make it also clear that since we have to ensure that the particle takes away energy from the star it cannot be produced almost at rest. The analysis becomes then a little bit more involved as we will have to start with an assumed value of $m_{\mathcal{S}/\mathcal{P}}$, typically $m_{\mathcal{S}/\mathcal{P}} \simeq 10^{-1}T_{star}$, corresponding to $\left(\frac{m_{\tilde{\gamma}}}{m_{3/2}}\right) \simeq 10^{12}\left(\frac{T_{star}}{keV}\right)$, put the limit through exotic cooling on $m_{\mathcal{S}/\mathcal{P}}$ (alternatively on $\left(\frac{m_{\tilde{\gamma}}}{m_{3/2}}\right)$) and finally check if the bound so obtained is better than the starting assumption. Similar method has been used in [25] for constraining the $\gamma\gamma$ coupling of a light pseudoscalar particle from the physics of pulsars. For consistency reasons there one starts with a mass smaller than $10^{-10}\ eV$. If the two photon coupling depends upon mass, as it is the case for axions in a model dependent way, one has then to check, from model to model, if the bound on the particle mass so derived is better than $10^{-10}\ eV$.

The first process of interest in our case is the Primakoff reaction $\gamma Z \to Z\mathcal{S},\ Z\mathcal{P}$ with $Z = e,\ p$. In the range $m_Z >> \omega_\gamma >> \omega'$ one obtains

$$\frac{\sigma_\gamma}{2} \equiv \sigma(\gamma Z \to Z\mathcal{S}) = \sigma(\gamma Z \to Z\mathcal{P}) = \frac{\kappa^2\alpha_{em}}{6}\left(\frac{m_{\tilde{\gamma}}}{m_{3/2}}\right)^2\left\{2\ln\left(\frac{\omega_\gamma}{m_{\mathcal{S}/\mathcal{P}}}\right) + 2\ln 2 - 1\right\} \tag{8}$$

In the approximation we have used the cross section of the Primakoff process is independent of the target mass and is the same for spin-0 target (relevant for Helium burning stars). Note also that the cross section becomes singular as $m_{\mathcal{S}/\mathcal{P}} \to 0$.

The sum of the cross sections for all possible $\gamma\gamma$-scatterings in the limit $\omega_\gamma >> m_{\mathcal{S}/\mathcal{P}},\ m_{3/2}$ reads [9]

$$\sigma_{\gamma\gamma} = \sum_{X=\mathcal{SS},\mathcal{PP},\mathcal{SP},\tilde{G}\tilde{G}} \sigma(\gamma\gamma \to X) = \frac{7}{216\pi}\kappa^4 \left(\frac{m_{\tilde{\gamma}}}{m_{3/2}}\right)^4 \omega_\gamma^2 \tag{9}$$

The exact calculation of an energy loss ($\dot{\epsilon}$) per unit mass and unit time involves an integration over the initial momenta of the squared matrix element folded with the Bose-Einstein or Fermi-Dirac distribution and taking into account the chemical composition of the star and possible Pauli blocking [22]. Here we will adopt a simplified version which is sufficient for our purposes and should give the correct results for stars like the Sun and Red Giants. We can write the exotic cooling rates due to the single and two photon reactions as

$$\dot{\epsilon}_\gamma = \frac{n_e n_\gamma \sigma_\gamma \omega'}{\varrho} \quad + \quad \frac{n_p n_\gamma \sigma_\gamma \omega'}{\varrho} \tag{10}$$

$$\dot{\epsilon}_{\gamma\gamma} = \frac{2n_\gamma^2 \sigma_{\gamma\gamma}\omega'}{\varrho} \tag{11}$$

where ϱ is the core density of the star and n_X is the number density of the particle species $\gamma,\ e,\ p$. The factor 2 appears in eq.(11) because two particles are emitted. With $\omega_\gamma \sim \omega' \sim T$ and $\varrho \simeq n_p m_N$ (m_N is the nucleon mass) one obtains

$$\begin{aligned}\dot{\epsilon}_\gamma &\simeq \frac{4\zeta(3)}{3\pi^2}\alpha_{em}\frac{\kappa^2}{m_N}\left(\frac{m_{\tilde{\gamma}}}{m_{3/2}}\right)^2 T^4 \left\{2\ln\left(\frac{T}{m_{\mathcal{S/P}}}\right) + 2\ln 2 - 1\right\} \\ &\sim \frac{\zeta(3)}{27\pi^2}\alpha_{em}\frac{m_{\mathcal{S/P}}^2}{\Lambda_{QCD}^4 m_N} T^4 \left\{2\ln\left(\frac{T}{m_{\mathcal{S/P}}}\right) + 2\ln 2 - 1\right\}\end{aligned} \tag{12}$$

$$\dot{\epsilon}_{\gamma\gamma} \simeq \frac{7}{27}\frac{\zeta^2(3)}{\pi^5}\frac{T^9}{\varrho}\kappa^4\left(\frac{m_{\tilde{\gamma}}}{m_{3/2}}\right)^4 \sim \frac{7}{34992}\frac{\zeta^2(3)}{\pi^5}\frac{T^9 m_{\mathcal{S/P}}^4}{\varrho\Lambda_{QCD}^4} \tag{13}$$

where ζ is Riemann's zeta function.

The bound on $\left(\frac{m_{\tilde{\gamma}}}{m_{3/2}}\right)$ can be obtained now from eqs.(12) and (13) by imposing $\dot{\epsilon}_\gamma,\ \dot{\epsilon}_{\gamma\gamma} < \dot{\epsilon}_{star}$. The set of astrophysical parameters needed in the analysis are as follows: $T_\odot \simeq 1\ keV,\ \varrho_\odot \simeq 10^2 g\ cm^{-3},\ \dot{\epsilon}_\odot \simeq 17.5\ erg\ g^{-1}\ sec^{-1}$ and $T_{RG} \simeq 10\ keV$,

$\varrho_{RG} \simeq 10^4\ g\ cm^{-3}$, $\dot{\epsilon}_{RG} \simeq 10^2 erg\ g^{-1}\ sec^{-1}$. As explained above one assumes a starting value, $m_{\mathcal{S}/\mathcal{P}} \simeq 10^{-1} T_{star}$ or equivalently $\left(\frac{m_{\tilde{\gamma}}}{m_{3/2}}\right) \simeq 10^{12} \left(\frac{T_{star}}{keV}\right)$, which is consistent with temperature of the Sun and the decay lifetime of the particle. The bound we obtain this way from eq.(12) is for the Sun $\left(\frac{m_{\tilde{\gamma}}}{m_{3/2}}\right)_{\odot} < 2.4 \times 10^9$ and for the Red Giants $\left(\frac{m_{\tilde{\gamma}}}{m_{3/2}}\right)_{RG} < 6 \times 10^7$. Indeed the analysis is consistent since the bound so obtained is orders of magnitude stronger than the starting value. One can also perform a slightly better analysis by an iteration process. Translating the bound on $\left(\frac{m_{\tilde{\gamma}}}{m_{3/2}}\right)$ into the corresponding value of $m_{\mathcal{S}/\mathcal{P}}$ one can insert the latter back into eq.(12) and proceed till a convergence is reached. Note that the convergence is then independent whether one starts with $m_{\mathcal{S}/\mathcal{P}} \simeq 10^{-1} T_{star}$ or $m_{\mathcal{S}/\mathcal{P}} \simeq 10^{-2} T_{star}$. As a check one can use the second form of eq.(12) expressed in $m_{\mathcal{S}/\mathcal{P}}$. The conclusion is then that the following region is excluded

$$1.8 \times 10^9 \ \not< \ \left(\frac{m_{\tilde{\gamma}}}{m_{3/2}}\right)_{\odot} \ \not< \ 10^{12}, \qquad 3.3 \times 10^7 \ \not< \ \left(\frac{m_{\tilde{\gamma}}}{m_{3/2}}\right)_{RG} \ \not< \ 10^{13} \qquad (14)$$

These limits justify our analysis as it excludes huge range of the parameter space. On the other hand in view of the first (second) bound in eq.(4) it also means that the range of $\left(\frac{m_{\tilde{\gamma}}}{m_{3/2}}\right)$ between 10^{13} and 1.8×10^{15} (10^{13} and 4.5×10^{13}) remains unrestricted by our analysis. It is worth emphasizing that taking the bound from $p\bar{p}$ colliders and combining it with eq.(14) this window of allowed values becomes quite narrow.

Let us also make a rough estimate of what is to be expected for a White Dwarf ($T_{WD} \simeq 2\ keV$, $\varrho_{WD} \simeq 10^5 g\ cm^{-3}$, $\dot{\epsilon}_{WD} \simeq 5 \times 10^{-3} erg\ g^{-1} sec^{-1}$). Here the plasmon effects play a non-negligible role and can be taken into account approximately by multiplying $\dot{\epsilon}_\gamma$ by the suppression factor $e^{-m_*/T}$ where m_* is the plasmon mass. As compared to the Sun the gain/loss factor is $\left[\left(\frac{T_{WD}}{T_\odot}\right)^4 \left(\frac{\dot{\epsilon}_\odot}{\dot{\epsilon}_{WD}}\right) e^{-m_*/T_{WD}}\right]^{-1/2} \sim 1.2 \times 10^{-2}$ for $m_*/T_{WD} \sim 2$. Roughly speaking

the bound from White Dwarfs is not expected to be better than the one obtained already for Red Giants.

The two gamma cooling rate is, as one can see from eq.(13), very sensitive to the temperature. However, even for stars with high core temperature this cannot overcome the other small factors, like κ^4, to make the rate appreciable. For the Sun the limit one gets from eq.(13) is $m_{\mathcal{S}/\mathcal{P}} < 3\times 10^5\ keV$ which is clearly not a useful bound at all. For a Supernova ($T_{SN} \simeq 30\ MeV$, $\varrho_{SN} \simeq 10^{12} g\ cm^{-3}$, $\dot{\epsilon}_{SN} \simeq 3.6\times 10^{19} g\ cm^{-3}$) the gain loss factor is $\left[\left(\frac{T_{SN}}{T_\odot}\right)^9 \left(\frac{\varrho_\odot}{\varrho_{SN}}\right)\left(\frac{\dot{\epsilon}_\odot}{\dot{\epsilon}_{SN}}\right) e^{-2m_*/T_{SN}}\right]^{-1/4} \sim 10^{-2}$ for $m_*/T_{WD} \sim 5$. This gives $m_{\mathcal{S}/\mathcal{P}} < 1\ MeV$ which is much weaker than the collider bound. Thus the Supernova analysis is not likely to provide a better bound than in eq.(14) (this is true for the processes we have investigated here, an additional process relevant for Supernova could be $e^+e^- \to \gamma^* \to \gamma + \mathcal{S}/\mathcal{P}$).

In conclusion, we have derived a bound on the ratio $\left(\frac{m_{\tilde{\gamma}}}{m_{3/2}}\right)$ which excludes values over several orders of magnitude. The window around $10^{12} - 10^{13}$ which our analysis leaves unconstrained can probably be closed in future collider experiments. In this case the absolute bound $\left(\frac{m_{\tilde{\gamma}}}{m_{3/2}}\right) < 3.3 \times 10^7$ could be put. With $m_{\tilde{g}} > 140\ GeV$ [26] this on the other hand would imply $m_{3/2} > 0.7\ keV$ which comes close to the bound from cosmology (eq.(5)) and hence leaves only a small window for light gravitino. Note that the inherent astrophysical uncertainties might introduce a certain margin of fluctuation of the numbers stated above, but the main conclusions remain unchanged.

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